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Experimental Performance Evaluation of Shape Memory Alloy (SMA) Compliant Micro Gripper for Micro Assembly

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This study introduces an innovative design for a compliant micro gripper based on Shape Memory Alloy (SMA) technology, intended for micro-assembly applications where SMA wire is used as an active actuator for opening and closing the jaw of micro gripper and gripping the object because it has a flexible behavior with high strength and large defection. This SMA wire can achieve the active actuator property by shape-changing properties with temperature. To control the temperature, the mathematical modeling and electro-mechanical characterizations of SMA wire are carried out by applying Joule's heating law method for identifying shape-changing properties with temperature. An experimental testing setup is also developed for characterizations of SMA wire where the behavior of SMA wire is controlled by setting the control parameters using the Lab VIEW software. After testing the SMA wires, the key finding is that the SMA wire shows steady-state behavior. Further, an SMA-based compliant micro gripper is developed. This development demonstrates that SMA wire facilitate the opening and closing of the jaws during the handling of miniature objects which shows that this flexible SMA-based micro gripper can be utilized in futuristic micro-assembly applications.

Keywords: Control system, Handling, Micro assembly, Micro gripper, SMA

Introduction

In the past, micro-robotic systems have been employed in both contact and contactless micro-nano manipulation techniques, such as micro grippers, micro-assembly, MEMS, scanning tunneling microscopy, nanotechnology, atomic force microscopy, optics etc.[1,2] These systems has the capability of handling and manipulating micron or sub-micron objects with significant accuracy at a low cost. Micro grippers, in particular, have demonstrated their versatility in applications like micro-assembly, materials science, robotics, cell manipulation, tissue engineering etc. Various micro-assembly tasks leverage intelligent material-based actuators, such as piezoelectric actuators, ionic polymer metal composite (IPMC), shape memory alloy (SMA), etc.[3–5] Each actuator type has its individual advantages and disadvantages. For example, IPMC actuators operate with small voltages (0–5VDC) and provide large displacements, but their sluggish response time limits their effectiveness in long-term micro gripping operations[6]. Piezoelectric actuators offer high micro/nano scale displacement but exhibit nonlinear deflection characteristics and require high voltage signals (0–60V).[7] Among these smart actuators, SMA's unique property is that it can the capability to return to a predefined shape by the heating-cooling/annealing process. They have shown an interesting deflection parameter as a direct function of temperature, deforming at low temperatures and maintaining this state until heated above a threshold temperature, at which point they instinctively return to their predefined shape with significant mechanical strength.[8] This property makes SMAs highly suitable for micro-robotics applications. SMA actuator wires achieve actuation through phase transformation in their crystal structure induced by temperature changes. Generally, hysteresis is observed in the SMA actuation behavior where the actuation behavior does not attain similar trends during the heating-cooling process due to the phase adjustment. This adversely affects the operation of the precise micro-assembly. So, controlling the actuation behavior of the SMA actuator is a challenging issue.[9,10] Conventional linear control cannot solve this problem. To address these challenges, we propose a novel design of a compliant micro gripper using an SMA active actuator for micro assembly in this paper. We experimentally control the actuation behavior of the SMA actuator, overcoming the limitations of conventional linear control methods.

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The major contribution/objective is highlighted point wise.

a) An innovative design of SMA based compliant micro gripper and characterization of SMA actuator behavior.

b) Experimental performance to obtain the deflection and load characteristics of SMA actuator.

c) Development and demonstration of SMA-based compliant micro gripper for micro assembly.

Brief State-of-art Report on SMA based Electromechanical System for Micro Assembly

Some researchers have been given their effort on different controlling methods of SMA for mechanical system applications previously. Dickinson *et al.*[11] have attempted the feedback controlling system for a beam using SMA by employing an SMA force/displacement model for stability analysis. Raparelli *et al.*[12] have designed a parallel SMA actuated robot where the robot has a parallel structure along with fixed and moving plates and these plates are linked together by the 3 SMA wires and a centrally located mechanical spring. Elahinia *et al.*[13] have concentrated on the nonlinear and robust control algorithms for the positioning of a 1 DOF SMA actuated rotary manipulator. Selden[14] has attempted the control of SMA actuators where the SMA wires are divided into multiple slices and the thermal states are individually controlled. Dutta *et al.*[15] have provided efforts on differential hysteresis modeling for the SMA wire actuator where the actuation goes through different physical phenomena like phase transformation with temperature hysteresis, heat transfer, electrical resistance variation, and stress-strain variations facilitating the phase transformation for SMA. Ahn *et al.*[16] have given an emphasis on a position control system for SMA actuation using a fuzzy set and PID controller where the control algorithms tune the PID control parameters by setting up the fuzzy parameters as an adaptive PID controller for self-tuning. Churchill *et al.*[17] have presented characterization techniques for measuring the strain of SMA wires, analyzing the characteristics of stresses and strains to understand their thermo-mechanical behavior Donmez *et al.*[18] have attempted on modeling, simulation, and experimental efforts to precisely control the position of SMA wires using various control methods. After study, the best control systems are applied in robotic applications such as flexible manipulator and grippers. Liu *et al.*[19] have attempted on self-sensing feedback control methodology for SMA actuators with the thermodynamics effects whereas Shibly *et al.*[20] have provided efforts towards the mathematical modeling of SMA behavior for online and rapid hysteresis prediction where the heating-cooling process is conducted under a fixed load conditions and the hysteretic behavior prediction is realized through the model's adaptation. Donmez *et al.*[21] have emphasized the design and control of SMA wires for flap-type aerodynamic surfaces whereas Barforoushi *et al.*[22] have attempted experimental modeling of an SMA where the model is based on customized Prandtle-Ishlinskii for a nonlinear block in series with linear block and unknown parameters of this model are computed with quadratic optimization method based on experimental results. Stirling *et al.*[23] have examined Ni-Ti SMA behavior by annealing process and developed an active system for the knee, where the controlled SMA springs are provided by using variable parameters like gait cycle, etc. Yan *et al*[24] have attempted on the passive control of steel structures using SMA wires, employing SMA as a passive damper to reduce dynamic responses under seismic loads. Wang *et al.*[25] have focused on a self-sensing controlled method for SMA where on base upon a certain pre-strain and duty cycle conditions. Bhargaw *et al.*[26] have presented the analysis of SMA wire for thermo-electric behavior and it shows a large mechanical force due to the change of phases. Malinga *et al.*[27] have focused on the fusion of an adaptive controller for an SMA actuated flexible beam whereas Mehrabi *et al.*[28] have focused on designing a micro gripper with an SMA actuator where the Finite Element Method (FEM) is carried out for calculating the stress distribution and deflection behavior.

Cecil *et al.*[29] have reviewed micro-device assembly techniques where various applications and associated challenges are discussed. Ruggeri *et al.*[30] have focused on different micro-assembly methods such as automated handling of components, sub-micron precision, and dominance of surface forces, etc. which can perform the work cell tasks during operations. Roshan *et al.*[31] have focused on a surgical device featuring a customized SMA spring actuator where a testing setup is designed to analyze the force-sensing elements of the SMA. Ren *et al.*[32] have attempted an SMA actuator and sensor for controlling the closed-loop system where the actuator shows dynamically cyclic actuation and the embedded sensor provides feedback during actuation. Shaikh *et al.*[33] have developed an SMA-actuated soft gripper where the performance of a two-finger gripper is analyzed using SMA actuators. Abdullah *et al.*[34] have attempted on SMA-based artificial muscle to develop a soft gripper where SMA fingers are fabricated where the actuation is provided for holding the spherical object. Scholtes *et al.*[35] have attempted the characterization of SMA wires for actuator and sensor applications where by changing the load and heating power, the different SMA wire models are trained. Xu *et al.*[36] have designed a passive variable stiffness-based SMA micro gripper where the compliant mechanisms are developed by controlling the constant force and its adjustment.

Based on the brief of literature survey, it is noted that SMA wire is not applied for developing the SMA-based compliant micro gripper which leads to the knowledge gap for developing such technology. Therefore, it is here proposed the novel design of SMA-based compliant micro gripper towards micro-assembly. A current relationship with time is obtained experimentally which helps in supplying the exact amount of current to SMA wire during handling operation. The force characteristic of SMA wires is also carried out by conducting experiments which helps in obtaining the stiffness of SMA towards the movement of the jaw while handling the object. This approach has made this study novel.

Design of SMA based Micro Gripper for Micro Manipulation

A novel compliant SMA-based gripper is intended as shown in Fig. 1. It features a link mechanism, spring arrangement, and SMA wire actuator. These compliant linkages are developed using a perspex sheet where hinge joints are also created which allows the links to rotate freely. A SMA wire is used between the linkage mechanisms for actuating the jaw of the micro gripper. The shape of the SMA wire has been given in a zigzag pattern by the annealing process so when it is activated, two jaws of micro gripper using the SMA actuator come closer. For activating the SMA wire, the current signal is supplied using Pulse Width Modulated (PWM) method to the SMA wire and it is heated according to the Joule heating effect. Here, the SMA wire shows the uni-directional behavior for providing the closing operation only of the jaw so the conventional two springs are used for providing restoring force towards opening the jaw of the micro gripper during the deactivation of the SMA wire. When the SMA wire is activated, the gripper jaw closes as the wire pulls the links and when the activation current is turned off, the springs pull it back to the opening position. During holding the object, spring stiffness plays a crucial role where the spring rate primarily dependent on its proportion. A decrease in the number of coils increases the spring stiffness. This stiffness can be adjusted using SMA wire, allowing for better control in holding the object which is described in result and discussion section.

A workflow diagram for the proposed methodology of the development of SMA-based complaint micro gripper is shown in Fig. 2. At first concept design of

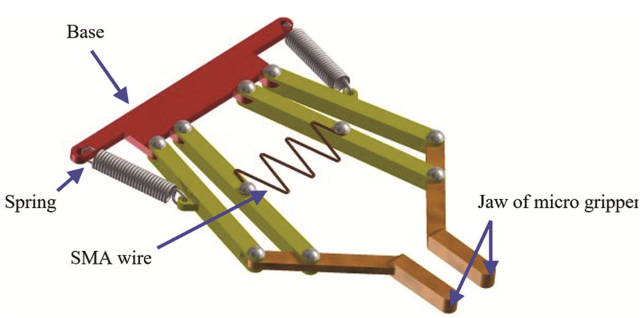


Fig. 1 — Design of SMA based compliant micro gripper

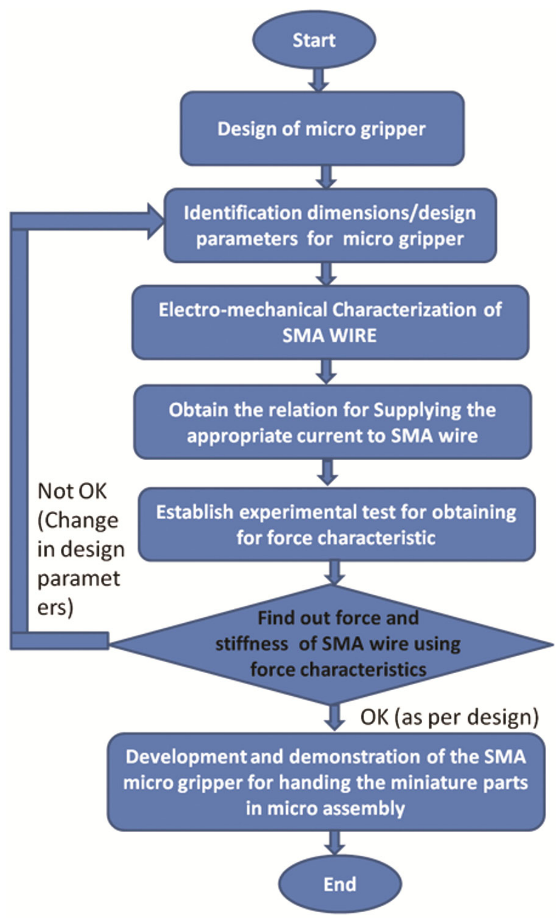


Fig. 2 — Work flow diagram for proposed methodology for design and development of SMA based complaint micro gripper towards micro assembly

SMA-based compliant micro gripper is developed using CAD software. Further, dimension and design parameters are identified for handling the object as listed in Table 1. In the next step, an electro-mechanical characterization of SMA wire is carried out to obtain the relationship of current with time which is supplied during the activation of SMA wire. Further, an experimental test setup is developed to obtain the force characteristics. After conducting experiments with SMA wire, the force characteristics with deflection are plotted and stiffness is found accordingly. If the handling of the force is sufficient then we can develop the SMA-based micro gripper for grasping the object. If the handling force is not sufficient then we have to change the dimensions and design parameters of the micro gripper to appropriate handling capabilities.

Mathematical Modeling for Electro-Mechanical Characterization of SMA Wire

To characterize the behavior of SMA wire, the design of actuator wire is considered based on SMA methodology[37] where the behavior of the SMA is taken linearly under the operating temperature range. For finding the temperature behavior by applying the voltage, the cross-sectional area of the circular wire (A) is considered as

$$A = \pi D^2/4 \quad \ldots (1)$$

By considering the stroke length of the wire as L, the total volume $V = A \times L$ and mass $m=d\times V=d\times A\times L$

To consider the change in temperature (ΔT) inside the material due to supplied heat Q is represented as

$$\Delta T = Q/mc \quad \ldots (2)$$

where, c is specific heat of SMA wire, m is mass of SMA wire

Table 1 — Detail about dimensions for design the micro gripper

S No	Parameters	Value
1.	Dimension of outer each links	30 mm
2.	Dimension of inner each links	40 mm
3.	Dimension of jaw each links	10 mm
4.	Width of micro gripper	30 mm
5.	Spring outer diameter	8 mm
6.	Diameter of SMA wire	0.3048 mm
7.	Applied voltage	12 V
8.	Method of applied voltage-current	PWM
9.	Young's Modulus of mild steel	200 GPa
10.	Tensile strength of SMA wire	754 – 960 MPa

By putting the values of ‘m’ and ‘c’, we get

$$\Delta T = Q/d \times A \times L \times c \quad \ldots (3)$$

Here, $\Delta T = T_e - T_r$ where T_r is room temperature/ reference temperature (°C) and T_e is temperature of material (°C) upon exciting by the current.

Temperature due to flow of the current is

$$T_e = \left[Q/(d \times A \times L \times c)\right] + T_r \quad \ldots (4)$$

According to Joule's law, heating effect (Q) of electric current can be written as

$$Q = I^2 R_L t \quad \ldots (5)$$

where, I is current flowing through a conductor of resistance R_L

The resistance is written in term of resistivity as

$$R_L = \rho L/A \quad \ldots (6)$$

where, ρ is density of material

Using Eqs (4–6), we got the relation between temperature and time because resistivity varies with temperature.

$$T_e = \left[I^2 \rho t/d \times A^2 \times c\right] + T_r \quad \ldots (7)$$

To find the resistivity in term of excitation temperature, experiments are conducted where SMA is heated and by increasing the temperature of SMA wire, the resistance value also increases. From, experimental values, the resistivity is found using LabVIEW software. After that, MatLab curve fitting tool is applied where the following data as given in Table 2.

The resistivity is found to be the function of temperature as given below

$$\rho = 3.219\times10^{-9} T_e^3 - 9.122\times10^{-7} T_e^2 + 1.648\times10^{-4} T_e + 6.871\times10^{-3} \quad \ldots (8)$$

Table 2 — Numerical data of SMA wire

S. No.	Parameter for analysis	Notation	Numerical value
1.	Diameter of SMA wire	D	0.3048 mm
2.	Applied voltage	v	12 V
3.	Current rating	I	1500 mA
4.	Room temperature	T_r	27°C
5.	Density	ρ	6.45 g/cm^3
6.	Specific heat	c	0.2 cal/g×°C

The relationship of SMA wire resistivity with the temperature is found using the experimental resistivity values with temperature in MATLAB using the curve fitting tool. Using this equation, the temperature is a function of time and resistivity when the applied current is constant. Therefore, the resistivity of the wire is also a function of temperature. Now, the present temperature (T_e) will affect future temperature (T_e+*1*) by changing the resistivity of the wire. For this reason, the temperature of the wire can be plotted as a function of time where the initial value of the temperature of the wire (T_r) should be given. Therefore, the incremental temperature is written as

$$T_{e+1} = \frac{I^2 \times (3.219\times10^{-9} T_e^3 - 9.122\times10^{-7} T_e^2 + 1.648\times10^{-4} T_e + 6.871\times10^{-3}) \times t}{d \times A^2 \times c} + T_r \quad \ldots (9)$$

After that, the behavior of SMA with excitation temperature and time is drawn as shown in Fig. 3. It reveals the temperature increase with time at a constant current value of 0.7 A. This shows the steady state behavior of the SMA actuator.

To find the current response with time for a constant voltage, the current through a resistive element of resistance R_L under excitation voltage (v) can be written as

$$I = v / R_L \quad \ldots (10)$$

Using Eqs (6–8), the current can be formulated in term of T_e as given below

$$I = \frac{v \times A}{(3.219\times10^{-9} T_e^3 - 9.122\times10^{-7} T_e^2 + 1.648\times10^{-4} T_e + 6.871\times10^{-3}) \times L} \quad \ldots (11)$$

Subsequently, the behavior of SMA with current response and time is also drawn as shown in Fig. 4. It reveals the current decrease with time at a constant voltage value of 1 V because resistance values increase by continuously increasing the excitation temperature of the SMA wire.

After obtaining the simulation results of temperature and current relation with times, an experimental setup is also developed for acquiring the experimental behavior of the SMA wire towards development of SMA based micro gripper for micro assembly.

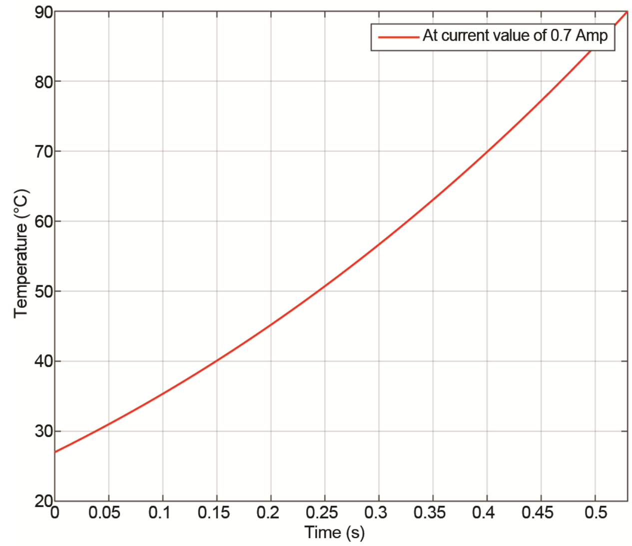


Fig. 3 — Plot between the temperature and time for excitation of SMA wire

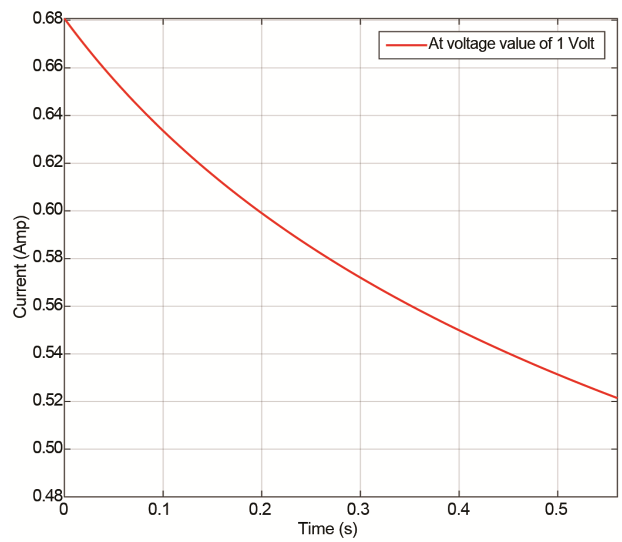


Fig. 4 — Relationship of current response and time

Experimental Testing Setup for SMA Wire

For characterization of an SMA actuator, this is fixed in a fixture with a zigzag pattern to get the desired shape. In this pattern, the both ends of SMA wire are fastened with the help of the nut-bolt arrangements as revealed in Fig. 5. The pattern along with the SMA wire is placed in furnace over 500°C up to 15 minutes for heating and then it is placed in water for cooling. To develop the testing setup of the SMA wire, this is placed inside the water container which is heated through an immersion heater. To measure the temperature of the SMA wire and water, a K-type thermocouple is dipped into the water. This

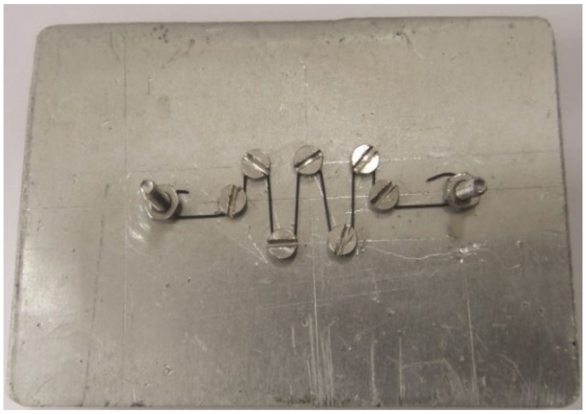


Fig. 5 — Pattern of SMA wire for characterization of an SMA actuator behaviour

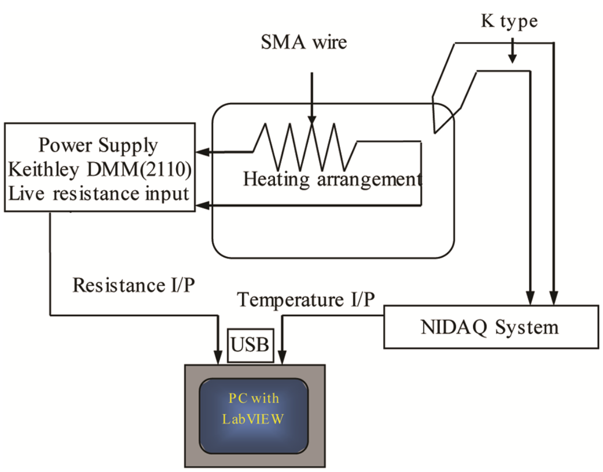


Fig. 6 — Schematic diagram for testing setup of SMA wire

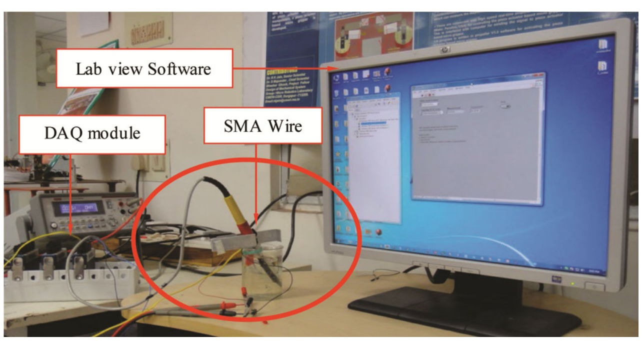


Fig. 7 — Actual test setup for temperature measurement of SMA wire

Table 3 — List of items used for experimentation

S. No.	Items	Quantity
1	SMA wire	01 Set
2	Power supply	01 Nos
3	PC with NI and Labview software	01 Nos
4	Thermocouple K-type	01 Set
5	Immersion heater	01 Nos
6	Wires	01 Set

thermocouple is interfaced with NI Controller (Model: 9211 module) with configurations of DAQ assistance in Lab VIEW software where the continuous sampling frequency configuration at 1Hz is considered. Along with this, to note the resistance value corresponding to the SMA temperature, the Digital Multimeter [Keithley DMM (Model 2110)] is also interfaced with Lab VIEW software in a two-wire measurement configuration via USB as revealed in Fig. 6. A Lab VIEW VI is designed in such a way that can take the values of temperature and resistance of SMA simultaneously. Using this setup, the temperature and resistance values are obtained continuously. While heating the water, SMA also gets heated and SMA wire temperature and resistance also increases accordingly.

The list of items is given in Table 3 which are used in experimental setups.

Results and Discussion

An experimental test setup is established as shown in Fig. 7. For finding the resistance of the SMA wire with the variation of temperature, the wire is dipped into the water which is being heated and a thermocouple is also dipped into the water to measure the temperature. The actuator wire ends are connected to the Digital Multi Meter (DMM) with the probes and clips. The SMA wire is heated through the hot water where the resistance value and corresponding temperature are measured. The heating of the SMA is done by placing the actuator into the water and then the water is heated. The water is heated with the immersion heater. The present water temperature is acquired with the K-type thermocouple (Make: Omega, USA) and the corresponding resistance value is achieved from the programmable DMM (Make: Keithley, USA). The thermocouple is connected with the NI-9211 module of NI-cDAQ (Model: NI-9172, Make: NI) and the DMM is connected with the PC through USB connectivity. One end of the thermocouple is dipped into the heated water and a further end is linked to the NI-9211 unit. This module is connected with the NI-PXI system as revealed in Fig. 8. A program is written in the LabVIEW software. It can store the temperature values from the thermocouple and corresponding resistance value from the DMM digital multi-meter. To communicate with the DMM, NI-VISA programming module is introduced in the LabVIEW software. Afterward, the temperature of the SMA and the corresponding resistance value are recorded into a measurement file. With the data of the measurement file, a plot of

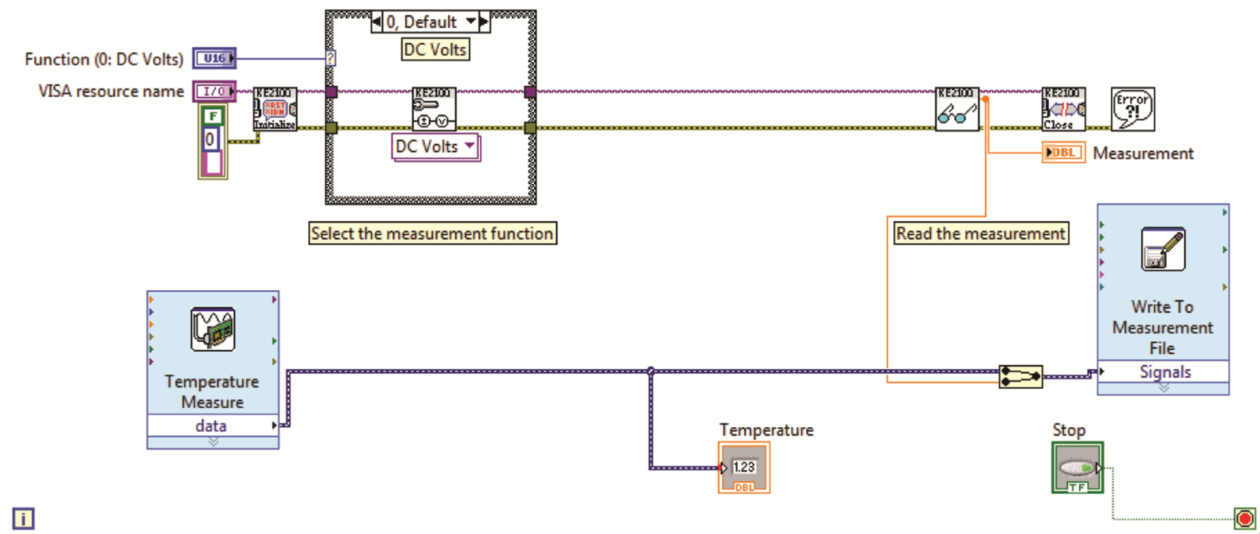


Fig. 8 — Flow diagram for temperature measurement of SMA wire

temperature versus resistance is generated in MATLAB software as presented in Fig. 9. It is found that the relation between temperature and resistivity shows exponential behavior when the applied current is constant.

For obtaining this temperature-resistivity relationship, a flowchart is prepared as given in Fig. 9. At first, the NI-9211 module is configured with K-type thermocouple and Keithley DMM via USB for measuring the resistivity and temperature of SMA wire respectively. After configuring the port, a program in LabVIEW software is developed to set proper instructions for obtaining the temperature and resistivity of the SMA. In this program, the maximum temperature value is set at 90°C. Online temperature value of the SMA actuator wire is acquired with the corresponding resistivity value accordingly. At last, the final temperature value attains 90°C as per the requirement of SMA wire.

For finding the measurement error in resistivity of SMA wire, the resistivity of the SMA wire actuator with temperature is obtained and several trials are conducted and experimental data are obtained as given in Table 4. From experimental data, the study shows that the standard deviation of resistivity is 0.0582 milliohm·m^{-1}. The normal distribution curve is also drawn in Fig. 10. This plot reveals that the standard deviation distribution is nearer to the tail which indicates the experimental data are appropriate and more reliable.

To analyze the force capacity of the SMA wire, the schematic and actual diagram for load testing is shown in Fig. 11. The wire is loaded with some

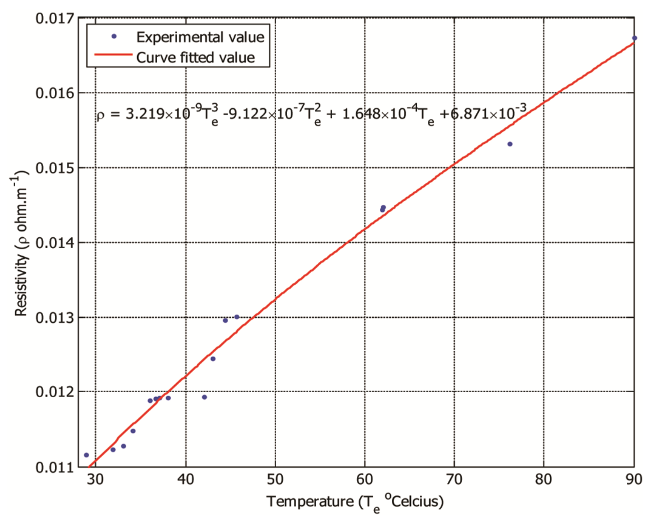


Fig. 9 — Relation of SMA wire resistivity with temperature

known weight and another end is connected with the load cell. This load cell can compute the force in Newton as connected to the other end.

A linear scale is placed for measuring the displacement and a camera is also used for monitoring the variation in the SMA wire length. The displacement of SMA wire contraction from the original length is measured by putting varied loads at the operating temperature (90°C) in an aqueous (water) environment. The temperature of the water is increased by immersion heater to attend to the actuation temperature of SMA dipped inside water. A K-type thermocouple is also used which records the temperature as connected through the NI-9211 module with data acquisition and LabView software. The experimental temperature value is recorded with this arrangement. By increasing

Table 4 — Experimental data of resistivity and variation of temperature

Number of trials		Temperature (°C)					
		28.9078	37.0647	43.0750	61.9429	76.1368	90
Resistivity (Ohm/m)	Trial1	0.01116	0.01200	0.01253	0.01440	0.01523	0.01670
	Trial2	0.01118	0.01200	0.01244	0.01440	0.01538	0.01671
	Trial3	0.01117	0.01181	0.01231	0.01440	0.01541	0.01681
	Trial4	0.0115	0.01190	0.01253	0.01452	0.01542	0.01670
	Trial5	0.01113	0.01191	0.01244	0.01452	0.01528	0.01668
	Trial6	0.01116	0.01211	0.01250	0.01437	0.01528	0.01680
	Trial7	0.01117	0.01210	0.01234	0.01448	0.01522	0.01663
	Trial8	0.01116	0.01162	0.01251	0.01429	0.01540	0.01678
	Trial9	0.01116	0.01183	0.01251	0.01450	0.01523	0.01671
	Trial10	0.01116	0.01174	0.01228	0.01442	0.01527	0.01678
	Average	0.01116	0.01190	0.01244	0.01443	0.01531	0.01673
Mean value (milliohm.m^{-1}) at actuating temperature (90°C)					16.7323		
Standard deviation (milliohm.m^{-1}) at actuating temperature (90°C)					0.0582		

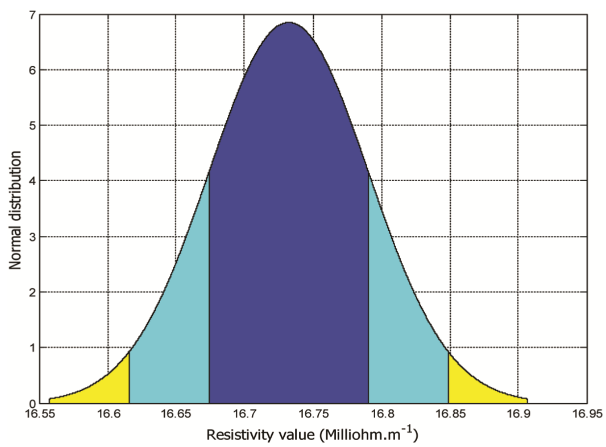


Fig. 10 — Normal distribution curve for SMA wire

the load from w_1 and w_2, the SMA wire is elongated as a spring with constant pull forces (F) and spring constant K from x_1 and x_2. The weight acts in the opposite direction of the pull and provides the resultant displacement.

$$F - w_1 = K \times x_1 \quad \ldots (12)$$

$$F - w_2 = K \times x_2 \quad \ldots (13)$$

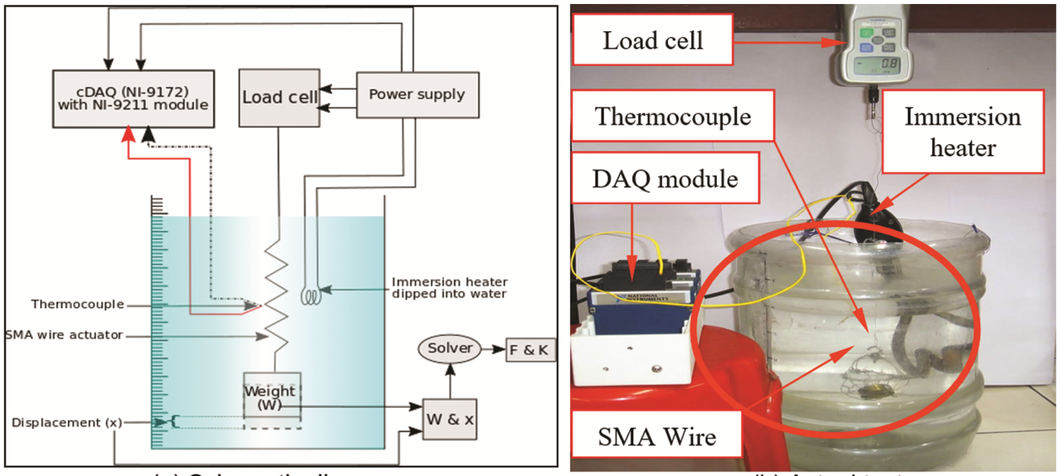
For analyzing the forces of SMA, the experiments are conducted in two sets where experiments are repeated 5 times with different weights in each set. These experimental data are used in the above equations for finding the two unknowns K and F. Using Matlab software, these data are drawn as shown in Fig. 12. It is found that the spring constant of the SMA wire is 0.1867 N/cm (Table 5). This will be helpful in the movement of the jaw during handling the object.

After these experimental studies, a micro gripper using SMA wire is developed as revealed in Fig. 13. This gripper is constructed with compliant links, hinge joints, springs, and SMA wire. All the links are made of compliant plastic materials. SMA wire is used for actuating the gripper whereas the springs provide the restoring force during un-gripping action. The gripping action is achieved with the SMA wire actuation using PWM voltage signal and the gripper holds the object. After deactivation of the SMA wire, the operation of jaw opening is performed with a restoring force provided by two springs, integrated with two extreme links of the gripper. During this operation, the SMA wire is forced to become in its original position.

For validation of experimental data, a comparison is carried out with design parameters of an SMA-based micro gripper as given in Table 6.

The above development of SMA based compliant micro gripper for micro assembly shows the following advantages and disadvantages. This gives the relevance to micro assembly.

- **Advantages:** The key advantages of SMA based compliant micro gripper are that it provides a large actuation force and compliant behavior while handling the object. Also, it has a high damping capacity and also provides high mechanical performance during operation.
- **Disadvantages:** The major disadvantages are that NiTi-based shape memory alloys are more expensive and hysteresis problems during handling operation.
- **Relevance to Micro-assembly**: The SMA-based compliant micro gripper is developed by using a compliant link mechanism, springs arrangement, and SMA wire actuator. The compliant/flexible



(a) Schematic diagram (b) Actual test

Fig. 11 — Testing setup for force analysis of SMA wire: (a) Schematic diagram, and (b) Actual test

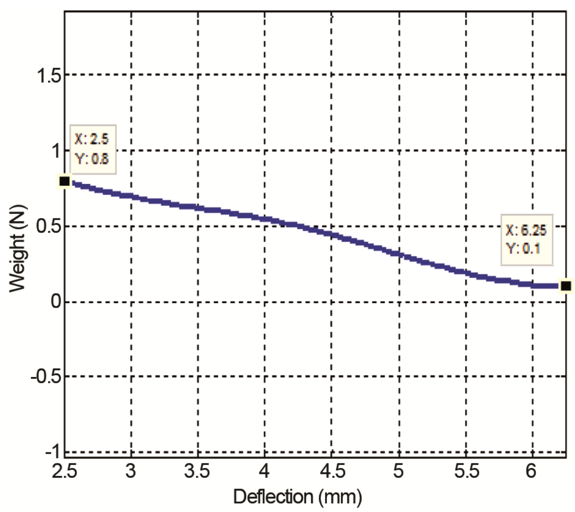
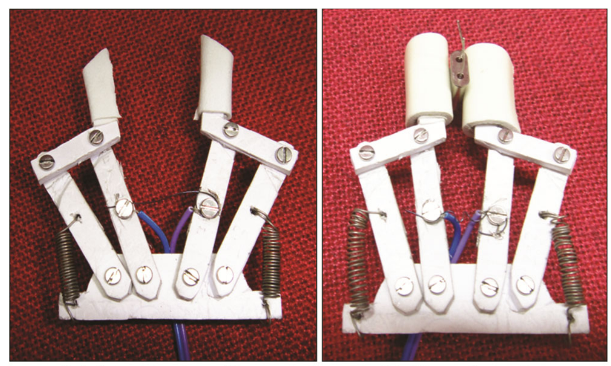


Fig. 12 — Experimental performance of SMA wire for spring constant

Table 5 — Experimental data for spring constant of SMA wire

Cases	Experiment No	Weight (N)	Deflection (mm)	Force (N)	Spring constant (N/mm)
Set 1	1	0.1	6.2		
	2	0.2	5.5	1.2730	0.1867
	3	0.5	4.2		
	4	0.6	3.7		
	5	0.8	2.5		
Set 2	1	0.2	5.4		
	2	0.5	4.3		
	3	0.8	2.5		
	4	0.6	3.6		
	5	0.1	6.3		

linkages provide more flexibility during the handling of the small/miniature object. The micro gripper for micro assembly is developed using SMA wires and the jaw of the gripper is actuated by changing the shape of the SMA wire actuator which is controlled by a customized voltage-current system.



(a) Jaw open position (b) Closed position

Fig. 13 — Development of SMA wire based micro gripper. (a) Jaw open position; and (b) Closed position

The novelty of the manuscript is highlighted pointy wise:

- An innovative design of SMA based micro gripper is proposed where SMA wire is used for controlling the jaw of the micro gripper because during handling the object, the SMA wire is activated, the gripper jaw closes as the wire pulls the links and when the activation current is turned off, the springs pull it back to the opening position which this kind of concept shows the novel concept of micro gripper with handling lightweight object.
- An electro-mechanical characterization of SMA wire is also attempted where the current relationship with time is obtained experimentally which helps in supplying the exact amount of

Table 6 — A comparison of design parameters for an SMA-based micro gripper

Parameter	Present study	Chandan *et al.*[38]
Type of mechanism for gripper	Modified four bar mechanism for one jaw	Slider crank mechanism
Spring outer diameter (Mild steel)	1 mm	1 mm
Force obtained by SMA	1.2730 N	0.66 N
Stiffness constant of SMA	0.1867 N/mm	0.0.91 N/mm
Maximum defection of SMA	6.3 mm	7.2 mm
Maximum temperature attained by SMA	90°C	90°C

current to SMA wire during handling the object.

- The force characteristic of SMA wires is found by conducting experiments which helps in obtaining the stiffness of SMA. This will be helpful in the movement of the jaw during handling the object.
- A prototype of SMA based micro gripper is developed and demonstrates of handling capabilities of miniature/tiny components in micro assembly.

Conclusions

This paper discusses an innovative design of an SMA-based compliant micro gripper for handling miniature objects, utilizing an SMA wire as an active actuator. This actuator functions as a spring, enabling the opening and closing of the micro gripper's jaws, thus providing compliance during object handling and assembly. Characterization of the SMA wire actuator revealed that it can reach a maximum temperature of 90°C and demonstrates the steady-state behavior which is measured by a K-type thermocouple. Experimental results reveal that the SMA wire has a maximum load-carrying capability of up to 1.2730 N. We also developed an SMA wire-based compliant micro gripper where the jaw movement is controlled by the SMA wire actuator. This micro gripper effectively handles miniature electronic and mechanical components such as transistors, ICs, small nuts, and bolts. The study demonstrates that the SMA-based compliant micro gripper is suitable for grasping and handling miniature/tiny parts with compliance in micro-assembly tasks. Future work involves integrating this SMA-based compliant micro gripper with a miniature manipulator to demonstrate desktop micro-assembly capabilities.

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